PROCEEDINGS OF SCIENCE

PoS(NuFact08)022

Prospects for mass scale and inverted hierarchy in non oscillations experiments

SILVIA PASCOLI*

IPPP, Dept. of Physics, Durham University, South Road, Durham, UK

E-mail: silvia.pascoli@durham.ac.uk

After the recent evidence of neutrino oscillations which imply the existence of neutrino masses and mixing, one of the most compelling questions in neutrino physics concerns the determination of the absolute values of neutrino masses. Various experimental strategies are and will be employed to answer this question. Here, I will review the non-oscillation techniques for neutrino mass determination with specific emphasis on direct neutrino mass searches and neutrinoless double beta decay.

10th International Workshop on Neutrino Factories, Super beams and Beta beams
June 30 - July 5 2008
Valencia, Spain

*Speaker.

1. Introduction

The interpretation of the solar and atmospheric neutrino, of the KamLAND and of the K2K and MINOS data (for a recent review see Ref. [1]) in terms of neutrino oscillations requires the existence of neutrino masses and mixing. The relation between the three left-handed flavour neutrino fields $\nu_{l\mathrm{L}}$ and the massive eigenstates ν_j, with a mass m_j, is described by a unitary 3×3 mixing matrix called the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) U [2] as:

$$\nu_{l\mathrm{L}} = \sum_{j=1}^{3} U_{lj}\, \nu_{j\mathrm{L}} \ . \tag{1.1}$$

The PMNS matrix can be parametrized by 3 angles, and, depending on whether the massive neutrinos ν_j are Dirac or Majorana particles, by 1 or 3 CP-violation (CPV) phases [3, 4] as:

$$U_{\mathrm{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \cdot \mathrm{diag}(1, e^{i\frac{\alpha_{21}}{2}}, e^{i\frac{\alpha_{31}}{2}})\,, \tag{1.2}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, the angles θ_{ij}, $\delta = [0, 2\pi]$ is the Dirac CPV phase and α_{21}, α_{31} are two Majorana CPV phases [3, 4]. The parameters driving the solar (and KamLAND) oscillations are the mixing angle $\theta_{12} \equiv \theta_{\odot}$ and the mass squared difference $\Delta m^2_{21} = m^2_2 - m^2_1 \equiv \Delta m^2_{\odot}$, whose best fit values are $\sin^2\theta_{\odot} = 0.30$ and $\Delta m^2_{\odot} = 7.7\times 10^{-5}$ eV^2 [5]. The dominant $\nu_\mu \to \nu_\tau$ ($\bar{\nu}_\mu \to \bar{\nu}_\tau$) oscillations of atmospheric ν_μ ($\bar{\nu}_\mu$) is due to the neutrino mass squared difference $|\Delta m^2_{31}| = |m^2_3 - m^2_1| \equiv \Delta m^2_{\mathrm{A}}$ and the mixing angle $\theta_{23} \equiv \theta_{\mathrm{A}}$. Their best fit values are given by $|\Delta m^2_{\mathrm{A}}| = 2.4\times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$ [5]. The third angle present in the PMNS matrix, θ_{13}, is at present unknown with a tight bound coming from a combined analysis of oscillation data, $\sin^2\theta_{13} < 0.035$ (0.056) at 95% (99%) C.L. [5], although a recent hint in favour of $\theta_{13} \neq 0$ has been found [6].

The existing neutrino oscillation data allow us to determine $\Delta m^2_{\odot}$, $|\Delta m^2_{\mathrm{A}}|$, $\sin^2\theta_{\odot}$ and $\sin^2 2\theta_{\mathrm{A}}$ with a relatively good precision and to obtain rather stringent limits on $\sin^2\theta_{13}$. Despite these great achievements, we still lack important information on neutrino masses and mixing. The main goals of the next future program in neutrino physics concerns the determination of the nature of neutrino - whether they are Majorana or Dirac particles, of the value of θ_{13}, of the values of neutrino masses, of the presence of CP-violation in the lepton sector, and of the number of neutrinos. In the present proceedings, I will focus on the question of neutrino masses from the point of view of non-oscillation neutrino experiments and in particular I will discuss direct neutrino mass and neutrinoless double beta decay searches.

2. Neutrino masses

While the values of $\Delta m^2_{\odot}$ and of $|\Delta m^2_{\mathrm{A}}|$ are well known, the sign of Δm^2_{A} cannot be determined from the present (SK atmospheric neutrino, K2K and MINOS) data, which are well described by two-neutrino oscillations in vacuum. In the case of 3-ν mixing $\Delta m^2_{31} > 0$ or $\Delta m^2_{31} < 0$ correspond to two types of ν-mass ordering:

i) *with normal ordering*, $m_1 < m_2 < m_3$, $\Delta m^2_{\mathrm{A}} = \Delta m^2_{31} > 0$, and

ii) *with inverted ordering* $m_3 < m_1 < m_2$, $\Delta m^2_{\rm A} = \Delta m^2_{32} < 0$.
The three neutrino masses can be expressed in term of the lightest neutrino mass, $m_{\rm MIN}$, depending on the type of ordering as: i) Normal ordering: $m_1 = m_{\rm MIN}$, $m_2 = \sqrt{{m_{\rm MIN}}^2 + \Delta m^2_\odot}$, $m_3 = \sqrt{{m_{\rm MIN}}^2 + |\Delta m^2_{\rm A}|}$; ii) Inverted ordering: $m_3 = m_{\rm MIN}$, $m_1 \simeq m_2 = \sqrt{{m_{\rm MIN}}^2 + |\Delta m^2_{\rm A}|}$.

Conventionally, limiting cases for the values of $m_{\rm MIN}$ are taken, either $m_{\rm MIN} \ll \sqrt{\Delta m^2_\odot}, \sqrt{|\Delta m^2_{\rm A}|}$ or $m_{\rm MIN} \gg \sqrt{\Delta m^2_\odot}, \sqrt{|\Delta m^2_{\rm A}|}$ resulting into the types of neutrino mass spectra:
i) *Normal Hierarchical (NH)*: $m_1 \ll m_2 \ll m_3$, with $m_2 \cong \sqrt{\Delta m^2_\odot}$ eV and $m_3 \cong \sqrt{|\Delta m^2_{\rm A}|}$ eV; ii) *Inverted Hierarchical (IH)*: $m_3 \ll m_1 < m_2$, with $m_{1,2} \cong \sqrt{|\Delta m^2_{\rm A}|}$ eV; iii) *Quasi-Degenerate (QD)*: $m_1 \cong m_2 \cong m_3$, with $m_1 \cong m_2 \cong m_3 \cong m_0$, $m^2_j \gg |\Delta m^2_{\rm A}|$, $m_0 \gtrsim 0.10$ eV.

In order to measure neutrino masses, one will have to establish: 1) **the type of neutrino mass ordering**; 2) **the absolute neutrino mass scale, set by the value of** $m_{\rm MIN}$.
Various experimental strategies are employed for answering these questions:
i) *direct mass searches*. Tritium beta decay experiments can test the quasi-degenerate spectrum of neutrinos by looking at a deviation of the electron spectrum at the end point with respect to the massless neutrino case (see Sec. 3);
ii) *neutrinoless double beta-decay experiments*. This process takes place only if neutrinos are Majorana particles and lepton number is violated. The rate of the decay depends on the values of neutrino masses in a combination called the effective Majorana mass parameter, $|\langle m \rangle|$. In case of a positive signature, a measurement of $|\langle m \rangle|$ would allow to get information on the neutrino mass spectrum (see Sec. 4);
iii) *supernova neutrinos*. Once emitted in a supernova explosion, the neutrino wave-packet splits due to the small difference in velocity in its components and a time-spread in the signal in a neutrino detector would be recorded. Requiring the time-spread to be smaller than the time interval of the neutrino burst, it is possible to obtain a model-independent bound (see Ref. [7] and references therein):

$$m_\nu < E\sqrt{\frac{E}{\Delta E}\frac{\Delta T_{\rm obs}}{D}} \simeq 14 \text{ eV}\left(\frac{E}{10 \text{ MeV}}\right)\sqrt{\frac{E}{\Delta E}}\left(\frac{\Delta T_{\rm obs}}{10 \text{ sec}}\right)^{1/2}\left(\frac{50 \text{ kpc}}{D}\right)^{1/2}. \tag{2.1}$$

Supernova neutrinos can also reveal the type of neutrino ordering by looking at matter effects in neutrino oscillations (see, e.g. [8]).
iv) *cosmological observations*. The relic neutrinos, which remained in the Early Universe after neutrino decoupling at $T \sim 1$ MeV, were relativistic at the time of formation of the structures of the Universe, galaxies and clusters of galaxies, and therefore they are a component of hot dark matter. If their contribution to the energy density of the Universe is too large, the predictions of the models of structure formation cannot reproduce the cosmological observations. Very stringent bounds have been obtained, whose details depend on the set of cosmological data considered. Typically, one has $\sum_i m_i < 1.0$–1.5 eV (see, e.g. Ref. [9]).

3. Tritium beta decay and direct neutrino mass searches

As soon as the theory of β-decay was formulated, Fermi and Perrin proposed to measure the value of neutrino masses by looking at the high-end part of the electron β-decay spectrum. In the most sensitive experiments, the decay of tritium, ${}^3\mathrm{H} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$, is studied. The differential decay rate can be expressed as a sum over the decay rates into the final massive neutrinos:

$$\frac{d\Gamma}{dE} = \sum_i |U_{\mathrm{e}i}|^2 \frac{d\Gamma_i}{dE}, \tag{3.1}$$

where

$$\frac{d\Gamma_i}{dE} = Cp(E+m_e)(E_0-E)\sqrt{(E_0-E)^2 - m_i^2}F(E)\theta(E_0-E-m_i)\ . \tag{3.2}$$

Here m_e, p and E are the electron mass, momentum and energy, respectively, E_0 is the energy released in the decay, $F(E)$ takes into account the Coulomb interactions, and m_i *is the mass of the final antineutrino*. The constant C is given by $C \equiv G_F^2 m_e^3 \cos^2\theta_C |M|^2$, with G_F the Fermi constant and θ_C the Cabibbo angle. M is the constant nuclear matrix element. Depending on the type of neutrino mass spectrum, the electron spectrum will have a different dependence on neutrino masses [10]:

i) *NH spectrum*. In this case the contribution of the heaviest mass Δm_{A}^2 is suppressed in the decay rate by the small mixing $|U_{\mathrm{e}3}|^2$ and effectively the electron spectrum will correspond to the one for massless neutrinos:

$$\frac{d\Gamma}{dE} = \frac{d\Gamma_i(m_i=0)}{dE}. \tag{3.3}$$

ii) *IH spectrum*. In this case the contribution of Δm_{A}^2 is weighted by $|U_{\mathrm{e}1}|^2 + |U_{\mathrm{e}2}|^2 \simeq 1$ and the electron spectrum will have the form:

$$\frac{d\Gamma}{dE} = (1-|U_{\mathrm{e}3}|^2)\frac{d\Gamma_i(m_i=\Delta m_{\mathrm{A}}^2\ )}{dE} + |U_{\mathrm{e}3}|^2\frac{d\Gamma_i(m_i=0)}{dE} \simeq \frac{d\Gamma_i(m_i=\Delta m_{\mathrm{A}}^2\ )}{dE}\ . \tag{3.4}$$

iii) finally, *QD spectrum*. In this case, $m_1 \simeq m_2 \simeq m_3 \equiv m_0$ and the electron spectrum will be simply given by:

$$\frac{d\Gamma}{dE} = \frac{d\Gamma_i(m_i=m_0)}{dE}, \tag{3.5}$$

where we have used the fact that $|U_{\mathrm{e}1}|^2 + |U_{\mathrm{e}2}|^2 + |U_{\mathrm{e}3}|^2 = 1$.

It follows that beta-decay experiments can provide information on the neutrino mass spectrum and measure neutrino masses if the spectrum is QD and, possibly in the future, IH.

The present data from the Mainz [11] and Troitzk [12] experiments allow to constrain neutrino masses in the eV range (at 95% C.L.): $m_0 < 2.3$ eV. The KATRIN experiment [13] should be soon commissioned and in three years of data taking should improve the sensitivity down to $m_0 \sim 0.2$ eV, covering all the value of masses of the QD spectrum (for other beta-decay experiments see Ref. [14]).

4. Neutrinoless double beta decay

One of the most important questions to address in the future concerning massive neutrinos is whether they are Dirac or Majorana particles. The nature of neutrino is directly related to the fundamental symmetries of elementary particle interactions, and in particular to the conservation of the lepton number. The most sensitive probe of the nature of neutrinos is given by neutrinoless double beta-decay ($(\beta\beta)_{0\nu}$decay): a process in which two neutrons transform into two protons and two electrons, exchanging light virtual Majorana neutrinos.

The half-life of $(\beta\beta)_{0\nu}$-decay, $T_{\beta\beta_{0\nu}}$, depends on neutrino masses and mixing parameters via the effective Majorana mass $\langle m \rangle$ (see, e.g. Ref. [15]), $T_{\beta\beta_{0\nu}}^{-1/2} \sim <m> M$, where M is the corresponding nuclear matrix element (NME) and

$$|\langle m \rangle| \; = \left| m_1 |U_{\mathrm{e}1}|^2 + m_2 |U_{\mathrm{e}2}|^2 \; e^{i\alpha_{21}} + m_3 |U_{\mathrm{e}3}|^2 \; e^{i\alpha_{31}} \right| \; . \tag{4.1}$$

Here m_i denote the neutrino masses, $U_{\mathrm{e}i}$ the elements of the first row of U.

The extraction of $|\langle m \rangle|$ from a measurement of or a limit on $T_{\beta\beta_{0\nu}}$ depends on the theoretical evaluation of the NME. At present there are large uncertainties in their calculation and a strong theoretical effort is required in order to solve the problem of the computation of the nuclear matrix elements.

Rather stringent upper bounds on $|\langle m \rangle|$ have been obtained in the ^{76}Ge experiments by the Heidelberg-Moscow collaboration, $|\langle m \rangle| < 0.35$–$1.05$ eV (90% C.L.), and by the IGEX collaboration, $|\langle m \rangle| < (0.33$–$1.35)$ eV (90% C.L.). A positive signal at $> 6\sigma$, corresponding to $|\langle m \rangle| = 0.32 \pm 0.03$ eV, is claimed to have been observed [16]. At present NEMO3 [17] and CUORICINO [18] are taking data and, a part from NME uncertainties, should be able to check this claim. Their latest results read, at 90% C.L., $|\langle m \rangle| < (0.7$–$2.8)$ eV [17] and $|\langle m \rangle| < (0.2$–$0.9)$ eV [18]. In the future generation experiments CUORE, GERDA, EXO, MAJORANA, SuperNEMO, MOON, XMASS, CANDLES, aim at a sensitivity of $|\langle m \rangle| \sim (0.01 - 0.05)$ eV.

The predicted value of $|\langle m \rangle|$ depends, in the case of 3-ν mixing, critically on the neutrino mass spectrum and on the values of the two Majorana CP-violation phases in the PMNS matrix, α_{21} and α_{31} (see Eq. (4.1)) (see, e.g. Ref. [19]). We review here the predictions of $|\langle m \rangle|$ for the three conventional types of neutrino mass spectrum: NH, IH and QD, which are given by:

$$|\langle m \rangle|^{\mathrm{NH}} \simeq |\sqrt{\Delta m^2_\odot}\, \sin^2\theta_\odot \cos^2\theta_{13} + \sqrt{|\Delta m^2_{\mathrm{A}}|} \sin^2\theta_{13} e^{i\alpha_{32}}|, \tag{4.2}$$

$$|\langle m \rangle|^{\mathrm{IH}} \simeq \sqrt{|\Delta m^2_{\mathrm{A}}|} \cos^2\theta_{13} \sqrt{1 - \sin^2 2\theta_\odot \sin^2\left(\frac{\alpha_{21}}{2}\right)}, \tag{4.3}$$

$$|\langle m \rangle|^{\mathrm{QD}} \simeq m_0 |(\cos^2\theta_\odot + \sin^2\theta_\odot e^{i\alpha_{21}}) \cos^2\theta_{13} + e^{i\alpha_{31}} \sin^2\theta_{13}|, \tag{4.4}$$

where the notations are obvious.

It is possible to estimate the predicted values of $|\langle m \rangle|$ by substituting in Eqs. (4.2), (4.3) and (4.4) the present best fit values for $\Delta m^2_\odot$, Δm^2_{A}, $\theta_\odot$, and the prospective errors on the oscillation parameters. Here we take $\sigma(\Delta m^2_\odot) = 2\%$, $\sigma(\Delta m^2_{\mathrm{A}}) = 2\%$, $\sigma(\sin^2\theta_\odot) = 4\%$ and $\sigma(\sin^2\theta_{13}) = 0.006$. For an extended discussion, see the very recent analysis in Ref. [20]. For a typical value of $\sin^2\theta_{13} = 0.01$, we have $|\langle m \rangle|^{\mathrm{NH}}_{\mathrm{min}} = 1.5$ meV, $|\langle m \rangle|^{\mathrm{NH}}_{\mathrm{max}} = 3.9$ meV, $|\langle m \rangle|^{\mathrm{IH}}_{\mathrm{min}} = 15.0$ meV, $|\langle m \rangle|^{\mathrm{IH}}_{\mathrm{max}} = 50.0$ meV and $|\langle m \rangle|^{\mathrm{QD}}_{\mathrm{min}} = 60.7$.

As it was noticed in Ref. [21] (see also Ref.[19]), in the case of a *large but non-maximal solar mixing*, the predictions for the different type of neutrino mass spectra are very different. The crucial point is that, because of large but not-maximal solar mixing angle, a significant lower bound on $|\langle m \rangle|$ can be put in the case of the IH and QD spectra. More specifically, $|\langle m \rangle|$ is bounded to lie in the interval [19, 21]:

$$m_{\mathrm{MAX}} \cos 2\theta_\odot \lesssim |\langle m \rangle| \lesssim m_{\mathrm{MAX}}, \tag{4.5}$$

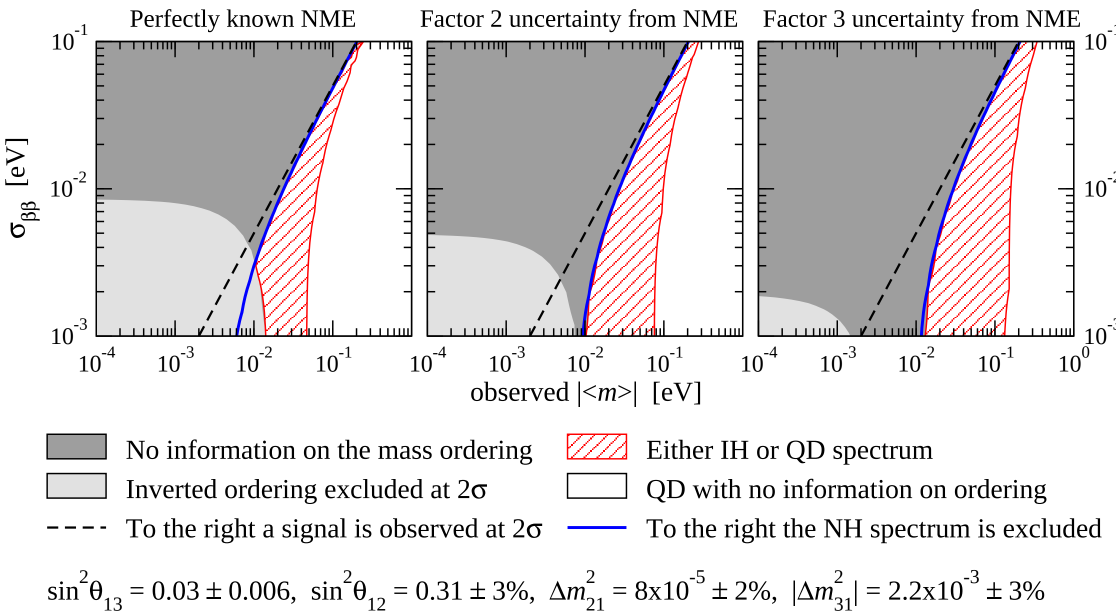

Figure 1: Information on the type of neutrino mass spectrum, inferred from data on $(\beta\beta)_{0\nu}$-decay as a function of the observed $|\langle m\rangle|$ and its experimental error for three different assumptions on the knowledge of the NME. For values of $|\langle m\rangle|^{\text{obs}}$ and of its experimental error, $\sigma_{\beta\beta}$, forming the dark shaded and white areas in the three panels, no information on $\text{sgn}(\Delta m^2_{31})$ can be obtained. The light shaded regions correspond to the case where $\text{sgn}(\Delta m^2_{31}) < 0$ (inverted mass ordering) can be excluded. Values of Δm^2_{A} $=$, $\Delta m^2_{\odot}$ $=$, $\theta_\odot =$ and $\sin^2\theta_{13} = 0.03$ were used. Figure taken from Ref. [22].

where $m_{\text{MAX}} \equiv \sqrt{|\Delta m^2_{\text{A}}|}$ for the IH spectrum and $m_{\text{MAX}} \equiv m_0$ for quasi-degenerate masses. The two limiting values correspond to CP-conservation: the upper (lower) bound is obtained for $\alpha_{21} = 0$ (π). This implies a significant lower bound on $|\langle m\rangle|^{\text{IH}} \gtrsim 15$ meV and $|\langle m\rangle|^{\text{QD}} \gtrsim 60$ meV, which is significantly larger then the upper bound on $|\langle m\rangle|$ for the NH spectrum. A detailed analysis of the capability of neutrinoless double beta decay in giving information on neutrino masses was performed in Ref. [22]. The prospective experimental errors were included as well the uncertainties on the nuclear matrix elements. In Fig. 1, taken from Ref. [22], I report the main conclusions on the determination of the neutrino mass spectrum. In the ideal case of perfectly known NME, a measurement of $|\langle m\rangle| > 0.1$ eV would typically imply that the spectrum is QD while for smaller values of $|\langle m\rangle|$ the dependence on the experimental error on $|\langle m\rangle|$ plays a relevant role. For an error of 10 meV, for $|\langle m\rangle| > 60$ meV the spectrum is established to be QD, while for 25 meV $<$ $|\langle m\rangle| < 60$ meV both IH and QD masses are allowed. Finally, for $|\langle m\rangle| < 25$ meV no information on the mass ordering would be found as the spectrum could be with normal ordering and partial hierarchy or inverted ordering. Similar, although somewhat weaker, conclusions can be drawn for larger uncertainties on the NME. It follows that the observation of $(\beta\beta)_{0\nu}$-decay could provide, in principle, unique information on the value of neutrino masses.

5. Conclusions

As neutrino oscillations have been established in the recent past, we now know that neutrinos have mass and they mix. Neutrino masses can follow two patterns: normal ordering if $m_1 < m_2 < m_3$ and inverted ordering for $m_3 < m_1 < m_2$. In order to establish the absolute values of neutrino masses it is necessary to determine the type of hierarchy and the absolute neutrino mass scale, set by the lightest neutrino mass, $m_{\rm MIN}$. Various experimental strategies are used to this aim, like direct mass searches by studying the electron spectrum in beta-decays, neutrinoless double beta decay by looking at the effective Majorana mass parameter, cosmological observation looking at the impact of neutrino masses on the structure formation in the Early Universe and on the Cosmic Microwave Background Radiation. Neutrino oscillations can also give information on the type of neutrino mass ordering by looking for matter effects in oscillations of supernova neutrinos, in long baseline experiments and atmospheric neutrinos. Here, I briefly reviewed the non-oscillation searches of neutrino masses.

These techniques will provide useful information on neutrino masses. They are complementary and their synergy should be used to achieve a better determination of mass and mixing parameters and to test the standard 3-neutrino mixing scheme. It should be noted that strong discrepancies in future data would be an indication that new physics effects, beyond the three-neutrino mixing scenario, are at work.

Acknowledgments

The author would like to thank the organisers for the very interesting conference and S. M. Bilenky, S. T. Petcov, T. Schwetz, W. Rodejohann for useful discussions.

References

[1] M. C. Gonzalez-Garcia and M. Maltoni, *Phenomenology with Massive Neutrinos*, *Phys. Rept.* **460** (2008) 1 [arXiv:0704.1800 [hep-ph]].

[2] B. Pontecorvo, *Zh. Eksp. Teor. Fiz.* **33** (1957) 549 and *Inverse beta processes and nonconservation of lepton charge*, *Zh. Eksp. Teor. Fiz.* **34** (1958) 247; Z. Maki, M. Nakagawa and S. Sakata, *Remarks on the unified model of elementary particle*, *Prog. Theor. Phys.* **28** (1962) 870.

[3] S.M. Bilenky, J. Hosek and S.T. Petcov, *On Oscillations of Neutrinos with Dirac and Majorana Masses*, *Phys. Lett.* **B94** (1980) 495.

[4] J. Schechter and J.W.F. Valle, *Neutrino Masses in SU(2) x U(1) Theories*, *Phys. Rev.* **D22** (1980) 2227; M. Doi *et al.*, *CP Violation in Majorana Neutrinos*, *Phys. Lett.* **B102** (1981) 323.

[5] T. Schwetz, M. Tortola and J. W. F. Valle, *Three-flavour neutrino oscillation update*, arXiv:0808.2016 [hep-ph].

[6] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo and A. M. Rotunno, *Hints of $\theta_1 3 > 0$ from global neutrino data analysis*, *Phys. Rev. Lett.* **101** (2008) 141801 [arXiv:0806.2649 [hep-ph]].

[7] S. M. Bilenky, C. Giunti, J. A. Grifols and E. Masso, *Absolute values of neutrino masses: Status and prospects*, *Phys. Rept.* **379** (2003) 69 [hep-ph/0211462].

[8] A. Dighe, *Physics potential of future supernova neutrino observations*, arXiv:0809.2977 [hep-ph]; C. Lunardini and A. Y. Smirnov, *Probing the neutrino mass hierarchy and the 13-mixing with supernovae*, *JCAP* **0306** (2003) 009 [arXiv:hep-ph/0302033].

[9] E. Komatsu et al. [WMAP Collaboration], *Five-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations:Cosmological Interpretation,* `arXiv:0803.0547 [astro-ph]`.

[10] S. M. Bilenky, M. D. Mateev and S. T. Petcov, *A comment on the measurement of neutrino masses in beta-decay experiments*, *Phys. Lett.* **B 639** (2006) 312 [`hep-ph/0603178`].

[11] Ch. Kraus et al., *Final results from phase II of the Mainz neutrino mass search in tritium beta decay, Eur. Phys. J.* **C40** (2005) 447 [`hep-ex/0412056]`.

[12] V. M. Lobashev et al. [Troitsk Coll.], *The search for the neutrino mass by direct method in the tritium beta-decay and perspectives of study it in the project KATRIN, Nucl. Phys.* **A 719** (2003) 153c.

[13] J. Wolf [KATRIN Coll.], *The KATRIN Neutrino Mass Experiment*, `arXiv:0810.3281 [physics.ins-det]`.

[14] C. Arnaboldi et al., *Bolometric bounds on the anti-neutrino mass, Phys. Rev. Lett.* **91** (2003) 161802; A. Monfardini et al., [MARE Coll.], *The Microcalorimeter arrays for a Rhenium experiment (MARE): A Next-generation calorimetric neutrino mass experiment*, *Prog. Part. Nucl. Phys.* **57** (2006) 68 [*Nucl. Instrum. Meth.* A **559** (2006) 346] [`hep-ex/0509038`].

[15] S. M. Bilenky and S. T. Petcov, *Massive Neutrinos and Neutrino Oscillations*, *Rev. Mod. Phys.* **59** (1987) 671.

[16] H. V. Klapdor-Kleingrothaus and I. V. Krivosheina, *The Evidence For The Observation Of 0nu Beta Beta Decay: The Identification Of 0nu Beta Beta Events From The Full Spectra, Mod. Phys. Lett.* A **21** (2006) 1547.

[17] J. S. Ricol [NEMO3 Coll.], *Results of the NEMO3 experiment*, `arXiv:hep-ex/0605104`.

[18] R. Maruyama [CUORICINO Coll.], *Cryogenic Double Beta Decay Experiments: CUORE and CUORICINO*, `arXiv:0809.3840 [nucl-ex]`.

[19] S.M. Bilenky, S. Pascoli and S.T. Petcov, *Majorana neutrinos, neutrino mass spectrum, CP violation and neutrinoless double beta decay. 1. The Three neutrino mixing case*, *Phys. Rev.* **D64** (2001) 053010 [`hep-ph/0102265`]. See also: S.M. Bilenky et al., *Short baseline neutrino oscillations and neutrinoless (Beta Beta) decay in schemes with an inverted mass spectrum*, *Phys. Rev.* **D54** (1996) 4432 [`hep-ph/9604364`]; S. M. Bilenky et al., *Constraints from neutrino oscillation experiments on the effective Majorana mass in neutrinoless double beta decay*, *Phys. Lett.* **B465** (1999) 193 [`hep-ph/9907234`]; V. Barger and K. Whisnant, *Majorana neutrino masses from neutrinoless double beta decay and cosmology*, *Phys. Lett.* **B456** (1999) 194 [`hep-ph/9904281`].

[20] S. Pascoli and S. T. Petcov, *Majorana Neutrinos, Neutrino Mass Spectrum and the* $|\langle m \rangle|$ $\tilde{0}$*.001 eV Frontier in Neutrinoless Double Beta Decay*, *Phys. Rev.* **D 77** (2008) 113003 [`arXiv:0711.4993 [hep-ph]`].

[21] S. Pascoli and S.T. Petcov, *The SNO solar neutrino data, neutrinoless double-beta decay and neutrino mass spectrum*, *Phys. Lett.* **B544** (2002) 239 [`hep-ph/0205022`].

[22] S. Pascoli, S. T. Petcov and T. Schwetz, *The absolute neutrino mass scale, neutrino mass spectrum, Majorana CP-violation and neutrinoless double-beta decay*, *Nucl. Phys.* **B 734** (2006) 24 [`hep-ph/0505226`].

PoS(NuFact08)022